

UNIT III – ENGINEERING MATERIALS**DIELECTRIC MATERIALS****Dielectric materials:**

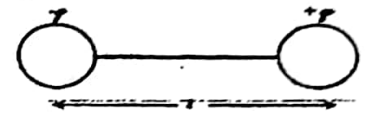
The Dielectric materials are electrically insulators. The electrons are tightly bound to the nucleus of the atom and there are no free electrons.

Ex: glass, mica, plastic, ebonite, rubber, wood, wax etc.,

- ❖ Dielectrics are non-metallic materials of high specific resistance and have negative temperature coefficient of resistance.
- ❖ If dielectric is used for insulation purpose then it is referred as insulating material but if it is employed for charge storage then it is referred to as dielectric.
- ❖ All dielectrics are insulators but all insulators are not dielectrics.

Definitions:

1. Electric dipole: Arrangement of two equal and opposite charges at a fixed distance is called electric dipole.



2. Electric dipole moment (μ): The product of magnitude of any one of the charge of the electric dipole and the distance between two charges is called electric dipole moment.

$$\mu = q \times \ell$$

It is vector quantity.

SI unit is coulomb-meter or Debye, 1 Debye = 3.3×10^{-30} C-m

3. Permittivity: It is the ability of a medium to allow electric lines of force to pass through it. It is the dielectric property of medium, which indicate the easily polarizable nature a material.

Unit: Fm^{-1} or $\text{C}^2/\text{N-m}^2$

4. Dielectric constant (Relative permittivity): It is defined as the ratio between permittivity of medium to the permittivity of free space.

$$K = \epsilon_r = \frac{\epsilon}{\epsilon_0}$$

It is dimensionless quantity and its value is 1 for vacuum. It is independent of size and shape of the dielectric.

It is also defined as the ratio of capacitance of a capacitor with dielectric to the capacitance of same capacitor without dielectric.

$$K = \epsilon_r = \frac{C}{C_0}$$

5. Electric polarization: When a dielectric material is placed inside an electric field dipoles are created in all the atoms inside the material.

The process of producing electric dipoles which are oriented along the field direction is called polarization.

6. Dielectric Polarizability (α): The dipole moment induced in an atom is proportional to electric field E .

$$\mu \propto E, \quad \mu = \alpha E, \quad \alpha = \frac{\mu}{E}$$

Where α is constant of proportionality known as polarizability.

The induced dipole moment per unit electric field is called as polarizability.

Unit: Cm^2/V or Fm^2

7. Dielectric polarization vector (P):

The electric dipole moment per unit volume is called electric polarization.

$$P = \frac{\mu}{V} = \frac{Ql}{Al} = \frac{Q}{A}$$

It is a vector quantity and its direction is along the direction of dipole moment.

If there are 'N' molecules per unit volume then polarization is $P = N\mu = N\alpha E$

SI unit: C/m^2

8. Electric field intensity (E): The force experienced by a unit positive charge placed at a point in the electric field is called electric field intensity.

It is a vector quantity.

SI unit: NC^{-1} or Vm^{-1}

$$E = \frac{F}{Q} = \frac{Q}{4\pi\epsilon_0 r^2}$$

9. Electric flux Density or Electric Displacement vector (D): The numbers of electric lines passing normally through a surface per unit cross sectional area. It is proportional to electric field intensity.

SI unit: C/m^2

$$D = \frac{Q}{4\pi r^2}$$

$$D \propto E$$

$$D = \epsilon E$$

$$D = \epsilon_0 \epsilon_r E$$

10. Electric susceptibility (χ_e):

The polarization vector p is proportional to applied electric field E

$$P \propto E$$

$$p = \epsilon_0 \chi_e E$$

Where, χ_e is called susceptibility of dielectric material.

It is defined as polarization per unit electric field intensity. It has no units.

Relation between D, E and P:

When a dielectric material is placed between plates of a charged capacitor then charges are induced on the surface of dielectric.

Let q' be induced charge on the dielectric and electric field (E') due to these charges is in opposite direction to electric field (E_0) due to charges on capacitor plates.

Resultant electric field between plates is $E = E_0 - E'$

Where $E_0 = \frac{Q}{\epsilon_0 A}$ and $E' = \frac{Q'}{\epsilon_0 A}$

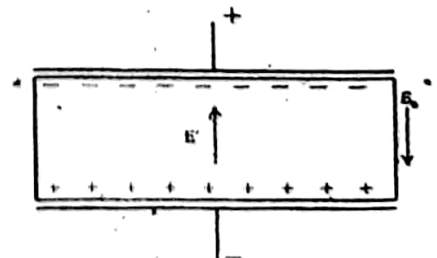
$$E = \frac{Q}{\epsilon_0 A} - \frac{Q'}{\epsilon_0 A}$$

$$\epsilon_0 E = \frac{Q}{A} - \frac{Q'}{A}$$

$$\epsilon_0 E = D - P$$

$$\text{Here } D = \frac{Q}{A} \text{ and } P = \frac{Q'}{A}$$

$$D = \epsilon_0 E + P$$



Relation between dielectric constant (ϵ_r) and electric susceptibility (χ_e):

We know electric displacement $D = \epsilon_0 E + P$

$$\text{But } D = \epsilon_0 \epsilon_r E$$

$$\epsilon_0 \epsilon_r E = \epsilon_0 E + P$$

$$P = \epsilon_0 \epsilon_r E - \epsilon_0 E$$

$$P = \epsilon_0 [\epsilon_r - 1] E$$

$$\frac{P}{\epsilon_0 E} = [\epsilon_r - 1]$$

$$\chi_e = [\epsilon_r - 1]$$

Types of polarizations: When a dielectric is placed inside an electric field Polarization occurs due to four types of processes. They are

- (i) Electronic polarization.
- (ii) Ionic polarization.
- (iii) Orientational polarization.
- (iv) Space charge polarization.

Q) Explain the electronic polarizability in atoms and obtain an expression for electronic polarizability in terms of radius of the atom.

Electronic polarization: When an electric field is applied to the dielectric, the displacement of positively charged nucleus and negatively charged electrons of an atom takes place in opposite directions. This results in electronic polarization. Therefore dipole is created within each atom and dipole moment is proportional to electric field strength.

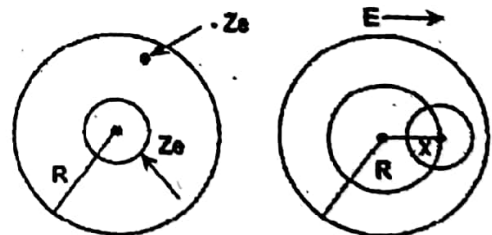
i.e., induced dipole moment, $\mu_e \propto E$

$$\mu_e = \alpha_e E$$

Where α_e is a constant called electronic polarizability. It exists at all frequencies and it presents in all types of dielectrics. Electronic polarizability increases with increasing volume of the atoms in the dielectric material and is independent of temperature.

Expression for electronic polarizability:

As shown in fig. Let us consider in an atom the nucleus of charge $+Ze$ is surrounded by an electron cloud if charge $-Ze$ distributed in a sphere of radius R . In the absence of electric field both the charge centers are coincide and no dipole is exist.



Charge density of sphere is equal to $\rho = \frac{-Ze}{\frac{4}{3}\pi R^3} = -\frac{3}{4}\left(\frac{Ze}{\pi R^3}\right)$

Where Ze is total charge inside the sphere of radius R .

But when electric field E is applied the nucleus and electrons experience Lorentz forces in the opposite directions. Hence nucleus and electron cloud are pulled apart. This results net dipole moment. When they are separated a Coulomb force develops between them, which tend to oppose the displacement. Under equilibrium these two forces are equal and opposite. Let the displacement be x under this condition.

Lorentz force between nucleus and electron cloud is $F_L = -ZeE$

The negative charge in the sphere of radius x is $= \frac{4}{3}\pi x^3 \rho$

$$= \frac{4}{3} \pi x^3 \left[-\frac{3}{4} \left(\frac{Ze}{\pi R^3} \right) \right] = - \left(\frac{Zex^3}{R^3} \right)$$

Coulomb force of attraction between the nucleus with charge Ze and the electron cloud at

a distance ' x ' from centre of nucleus is $F_c = \frac{Ze \left(-\frac{Zex^3}{R^3} \right)}{4\pi\epsilon_0 x^2} = -\frac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$

Under equilibrium condition,

$$F_L = F_c$$

$$ZeE = \frac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$$

$$E = \frac{Zex}{4\pi\epsilon_0 R^3}$$

$$x = \frac{4\pi\epsilon_0 R^3 E}{Ze} \dots\dots\dots (1)$$

Due to shifting of electron cloud, induced dipole moment is $\mu_e = Zex$

$$\mu_e = Ze \left(\frac{4\pi\epsilon_0 R^3 E}{Ze} \right)$$

$$\mu_e = 4\pi\epsilon_0 R^3 E \dots\dots\dots (2)$$

But, electronic polarizability of atom is $\mu_e = \alpha_e E \dots\dots\dots (3)$

Comparing eq.(2) and eq.(3), $\alpha_e = 4\pi\epsilon_0 R^3$

This is the expression for electronic polarizability.

Dipole moment per unit volume is called electronic polarization.

$$P_e = N\mu_e = N\alpha_e E$$

Where N is the number of atoms per unit volume.

But

$$P_e = \epsilon_0 [\epsilon_r - 1] E$$

$$\therefore N\alpha_e E = \epsilon_0 [\epsilon_r - 1] E$$

$$\alpha_e = \frac{\epsilon_0 [\epsilon_r - 1]}{N}$$

Q) What is ionic polarization? Derive the expression for ionic polarizability of ionic crystal.

Ionic polarization: The ionic polarization is due to displacement of cations and anions when an electric field is applied to a dielectric material. The ionic polarization occurs in ionic solids only. The induced dipole moment is proportional to applied field.

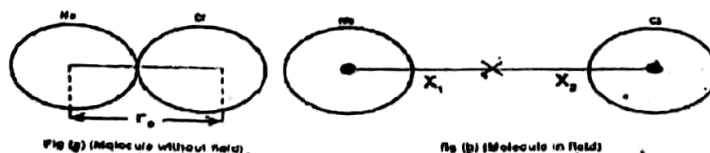
$$\text{i.e., } \mu_i \propto E$$

$$\mu_i = \alpha_i E$$

Where α_i is constant called ionic polarizability.

The induced dipole moment per unit electric field at the Ions is called ionic polarizability and corresponding polarization is called ionic polarization.

Expression for ionic polarizability:



When an electric field E is applied to an ionic crystal, positive ions are displaced through a distance X_1 in the direction of applied electric field and negative ions are displaced through a distance X_2 in opposite direction of electric field as shown in fig.

Distance between positive and negative ions is $X = X_1 + X_2$ (1)

Lorentz force acting on +ve Ions = Ee

Lorentz force acting on -Ve Ions = $-Ee$.

When ions are displaced from their mean position, a restoring force is developed on ions which move ions back to mean position.

Restoring force acting on positive Ions = $-K_1X_1$

Restoring force acting on negative Ions = K_2X_2

Where $K_1 = M\omega_o^2$ and $K_2 = m\omega_o^2$ are force constants; ω_o is angular velocity of ions, M and m are masses of +Ve and -Ve ions.

At equilibrium, Lorentz force and restoring force are equal and opposite.

$$\begin{aligned} \text{For positive ion, } Ee &= K_1X_1 \\ X_1 &= \frac{Ee}{K_1} = \frac{Ee}{M\omega_o^2} \dots\dots\dots(2) \end{aligned}$$

$$\begin{aligned} \text{For negative ion, } -Ee &= K_2X_2 \\ X_2 &= \frac{Ee}{K_2} = \frac{Ee}{m\omega_o^2} \dots\dots\dots(3) \end{aligned}$$

Substituting Eq(2) and (3) in Eq(1), we get

$$\begin{aligned} X &= \frac{Ee}{M\omega_o^2} + \frac{Ee}{m\omega_o^2} \\ X &= \frac{Ee}{\omega_o^2} \left(\frac{1}{M} + \frac{1}{m} \right) \end{aligned}$$

$$\text{Induced dipole moment is } \mu_i = eX = e \left[\frac{Ee}{\omega_o^2} \left(\frac{1}{M} + \frac{1}{m} \right) \right] = \frac{e^2E}{\omega_o^2} \left(\frac{1}{M} + \frac{1}{m} \right) \dots\dots\dots(4)$$

$$\text{But } \mu_i = \alpha_i E \dots\dots\dots(5)$$

$$\text{From Eq.(4) and (5), Ionic polarizability } \alpha_i = \frac{e^2}{\omega_o^2} \left(\frac{1}{M} + \frac{1}{m} \right)$$

Ionic polarizability is inversely proportional to square of the natural frequency of ionic molecule. It is independent of temperature.

Q) Define dipolar or orientational polarizability and show that it varies inversely with temperature.

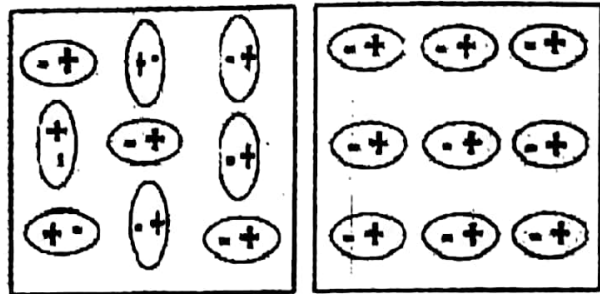
Orientalional or Dipolar.polarization:

The orientational polarization is a characteristic of polar dielectrics. In polar dielectric there are permanent dipole moments because positive and negative charges do not coincide in the molecules. Each molecule behaves as a dipole and all these dipoles are randomly oriented in the absence of electric field and net dipole moment is zero. But, when this polar dielectric is subjected to electric field the molecular dipoles tend to orient in direction of applied field as shown in fig.

The contribution to the polarization due to the orientation of molecular dipoles is called dipolar or orientational polarization. Dipole moment due to orientation of dipole is proportional to applied electric field.

$$\mu_o \propto E$$

$$\mu_o = \alpha_o E$$



Where α_o is called orientational polarizability.

It is given by $\alpha_o = \frac{\mu_o^2}{3K_B T}$

Where K_B is Boltzmann constant T is absolute temperature.

The orientational polarizability α_o is inversely proportional to the absolute temperature.

- ❖ **Space charge polarization:** Space charge polarization occurs in multiphase dielectric materials in which there is a change of resistivity between different phases. It is not an important factor in most common dielectrics.
- ❖ **Total polarization:** The total polarizability of a dielectric material is equal to sum of electronic, Ionic, orientational and space charge polarizabilities.

$$\alpha = \alpha_e + \alpha_i + \alpha_o + \alpha_s$$

Since space charge polarizability is very small compared to other polarizabilities,

$$\alpha = \alpha_e + \alpha_i + \alpha_o$$

$$\alpha = 4\pi\epsilon_o R^3 + \frac{e^2}{\omega_o^2} \left(\frac{1}{M} + \frac{1}{m} \right) + \frac{\mu_o^2}{3K_B T}$$

Total polarization of a dielectric material is $P = N \alpha E$

$$P = N \left[4\pi\epsilon_o R^3 + \frac{e^2}{\omega_o^2} \left(\frac{1}{M} + \frac{1}{m} \right) + \frac{\mu_o^2}{3K_B T} \right] E$$

This equation is known as Langevin-Debye equation.

Q) Derive expression for internal field seen by an atom in a dielectric field.

Lorentz Internal field or Local field or Lorentz field:

Internal field is the total electric field at an atomic site inside a dielectric material.

Internal field A is $E_1 = E_1 + E_2 + E_3 + E_4$ ----- (1)

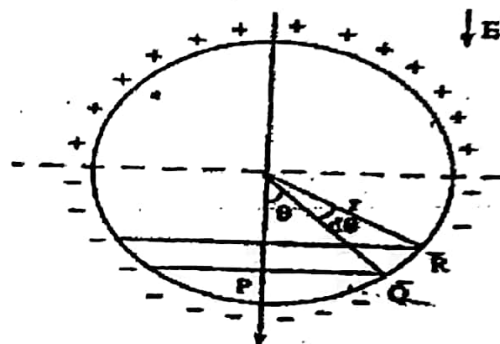
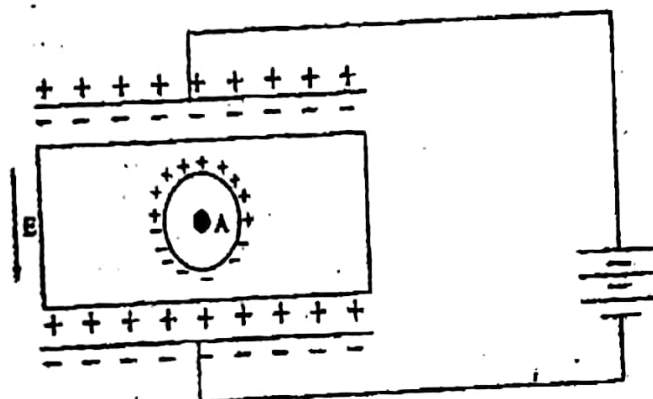
Where,

E_1 is field intensity due to charge density on plates

E_2 is field intensity due to charge density induced on two sides of dielectric

E_3 is field intensity due to other atoms in cavity and

E_4 is field intensity due to polarization charges on surface of cavity



Field E_1 : E_1 is field intensity due to charge density on plates

From the field theory

$$E_1 = \frac{D}{\epsilon_0}$$

$$\text{But, } D = P + \epsilon_0 E$$

$$\therefore E_1 = (P + \epsilon_0 E) / \epsilon_0 = E + P / \epsilon_0 \text{ -----(2)}$$

Field E_2 : E_2 is the field intensity at A due to charge density induced on two sides of dielectric

$$\therefore E_2 = - \frac{P}{\epsilon_0} \text{ -----(3)}$$

Field E_3 : E_3 is field intensity at A due to other atoms contained in the cavity and for a cubic structure,

$$E_3 = 0 \text{ because of symmetry -----(4)}$$

Field E_4 : E_4 is field intensity due to polarization charges on surface of cavity and was calculated by Lorentz in the following way:

If dA is the surface area of the sphere of radius r lying between θ and $(\theta + d\theta)$, where θ is the direction with reference to the direction of applied force.

Then

$$dA = 2 \pi (PQ) (QR)$$

But

$$\sin \theta = PQ/r \Rightarrow PQ = r \sin \theta$$

And

$$d\theta = QR/r \Rightarrow QR = r d\theta$$

Hence

$$dA = 2 \pi (r \sin \theta) (r d\theta) = 2 \pi r^2 \sin \theta d\theta$$

Charge on surface dA is

$$dq = P \cos\theta \, dA$$

$$dq = P \cos\theta (2\pi r^2 \sin\theta \, d\theta)$$

$$= P (2\pi r^2 \sin\theta \cos\theta \, d\theta)$$

The field due to the charge dq at A , is denoted by dE_4 in direction $\theta = 0$

$$dE_4 = (dq \cos\theta) / (4\pi\epsilon_0 r^2)$$

$$= [P(2\pi r^2 \sin\theta \cos\theta \, d\theta) \cos\theta] / (4\pi\epsilon_0 r^2)$$

$$dE_4 = (P \sin\theta \cos^2\theta \, d\theta) / 2\epsilon_0$$

$$E_4 = \int_0^\pi dE_4 = \int_0^\pi (P \sin\theta \cos^2\theta \, d\theta) / 2\epsilon_0$$

$$= \frac{P}{2\epsilon_0} \int_0^\pi (\sin\theta \cos^2\theta \, d\theta)$$

$$= \frac{P}{2\epsilon_0} \left(\frac{2}{3} \right)$$

$$\therefore E_4 = \frac{P}{3\epsilon_0} \text{ -----(5)}$$

Substituting Eqs. (2), (3), (4) & (5) in Eq.(1)

Local field

$$E_i = E_1 + E_2 + E_3 + E_4$$

$$= E + \frac{P}{\epsilon_0} - \frac{P}{\epsilon_0} + 0 + \frac{P}{3\epsilon_0}$$

$$\therefore \text{Local field } E_i = E + \frac{P}{3\epsilon_0} \text{ -----(6)}$$

Q) Derive Clausius – Mosotti equation.

Clausius – Mosotti equation: It gives the relation between dielectric constant and polarizability of atoms in a dielectric material. The dipole moment of a single atom is proportional to internal field i.e., $\mu = \alpha E_i$

Where α is polarizability of atom.

If there are N atoms per Unit volume, the dipole moment per unit volume called polarization is given by

$$P = N\alpha E_i \dots\dots\dots(1)$$

Where E_i is internal field of solid.

We know that,

$$E_i = E + \frac{P}{3\epsilon_0}$$

$$\therefore P = N\alpha_e \left[E + \frac{P}{3\epsilon_0} \right]$$

$$= \frac{N\alpha_e}{3\epsilon_0} [3\epsilon_0 E + P]$$

$$P = N\alpha_e E + P \frac{N\alpha_e}{3\epsilon_0}$$

$$P \left(1 - \frac{N\alpha_e}{3\epsilon_0} \right) = N\alpha_e E$$

$$P = (N\alpha_e E) / \left(1 - \frac{N\alpha_e}{3\epsilon_0} \right) \dots\dots\dots(2)$$

We know that

$$D = \epsilon_0 E + P$$

But

$$D = \epsilon_0 \epsilon_r E$$

$$\epsilon_0 \epsilon_r E = \epsilon_0 E + P$$

$$P = \epsilon_0 \epsilon_r E - \epsilon_0 E$$

$$P = \epsilon_0 [\epsilon_r - 1] E \dots\dots\dots(3)$$

From Eqs.(2) & (3)

$$\epsilon_0 [\epsilon_r - 1] E = (N\alpha_e E) / \left(1 - \frac{N\alpha_e}{3\epsilon_0} \right)$$

$$\left(1 - \frac{N\alpha_e}{3\epsilon_0} \right) = (N\alpha_e) / \epsilon_0 [\epsilon_r - 1]$$

$$1 - \frac{N\alpha_e}{3\epsilon_0} = (N\alpha_e) / \epsilon_0 [\epsilon_r - 1]$$

$$1 = \frac{N\alpha_e}{3\epsilon_0} \left[1 + \frac{3}{\epsilon_r - 1} \right]$$

$$1 = \frac{N\alpha_e}{3\epsilon_0} [(\epsilon_r - 1 + 3) / (\epsilon_r - 1)]$$

$$\frac{(\epsilon_r - 1)}{(\epsilon_r + 2)} = \frac{N\alpha_e}{3\epsilon_0}$$

This is Clausius – Mosotti equation.

Q) Mention the applications of dielectrics.

Applications of dielectrics:

Dielectrics are widely used as insulating materials.

1. Electrical conductors made of aluminium or copper used for electrical wiring are insulated with an outer jacket of plastic or rubber.
2. In heater coils, ceramic beads are used to avoid short circuiting and to insulate the outer body from current.
3. In electric iron, mica or asbestos insulation is used to prevent the flow of the current to the outer body.
4. In transformers, motors and generator windings, varnished cotton is used as insulator.
5. Dielectric materials are used as energy storage capacitors.
 - a. In capacitors with air as dielectrics are used in RF circuits.
 - b. In capacitors with mineral oil as dielectrics are used in high voltage applications.
 - c. In capacitors with solid as dielectrics are used in laboratories as standard capacitors.
6. Quartz crystal is used for the preparation of ultrasonic transducers, crystal oscillators, filters etc.,
7. Barium titanate is used for the preparation of accelerometers.
8. Lead zirconate titanate is used for the preparation of earphones, microphones, spark generators etc.,
9. The electro - optic devices are prepared using dielectric materials.

Questions

1. Define the terms i) Dielectric polarization ii) Dielectric Polarizability iii) Susceptibility iv) Dielectric constant
3. Explain the electronic polarizability in atoms and obtain an expression for electronic polarizability in terms of radius of the atom.
4. Define dipolar or orientational polarizability and show that it varies inversely with temperature.
5. What is ionic polarization? Derive the expression for ionic polarizability of ionic crystal
6. Mention the applications of dielectrics.
7. Derive expression for internal field seen by an atom in a dielectric field.
8. Derive clausius -mosotti equation

Problems

1. Polarizability of NH_3 molecule in gaseous state from the measurement of dielectric constant is found to be $2.5 \times 10^{-39} \text{ F-m}^2$ and $2 \times 10^{-39} \text{ F-m}^2$ at temperatures 300K and 400K respectively. Calculate the contribution to the polarizability because of deformation of molecules and the contribution because of permanent dipole moment at each temperature.
2. The radius of He atom is 0.55 Å. calculate the polarizability of He and its relative permittivity. The number of He atoms in a volume of 1 m^3 is 2.7×10^{25} atoms. The permittivity of free space is $8.85 \times 10^{-12} \text{ F/m}$.
3. The relative dielectric constant of sulphur is 3.75 when measured at 27° C calculate the electronic polarizability of sulphur if its density at this temperature is 2050 Kg/m^3 the atomic weight of sulphur is 32 amu.

Objective Questions

1. Dielectrics are

a) conducting materials	b) semi conducting materials
c) super conducting materials	d) insulating materials
2. Polarization is

a) dipole moment per unit volume	b) dipole moment per unit mass
c) dipole moment per unit area	d) none
3. Orientational polarizability is

a) directly proportional to temperature	b) inversely proportional to temperature
c) independent of temperature	d) none
4. The dipolar polarizability shows remarkable variations near the following frequencies

a) micro wave	b) infrared	c) ultraviolet	d) visible
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5. Ionic polarizability shows remarkable variations near the following frequencies

- a) micro wave b) infrared c) ultraviolet d) visible
6. Clausius Mosotti relation does not hold for
a) liquids b) gases c) amorphous solid d) crystalline solids
7. At low frequencies the following contributes to total polarizability is
a) electronic b) ionic c) Orientational d) all the above
8. The unit for permittivity of free space ϵ_0 is
a. Hm^{-1} b. Fm^{-1} c. Cm^{-1} d. dimensionless
9. Choose the correct relation
a. $E = \epsilon_0(\epsilon_r - 1)P$ b. $D = \epsilon_0(\epsilon_r - 1)E$ c. $P = \epsilon_0(\epsilon_r - 1)E$ d. $\epsilon_r = (\chi - 1)$
10. Choose the correct relation
a. $\chi_e = (\epsilon_r - 1)$ b. $\chi_e = (\epsilon_0 - 1)$ c. $\chi_e = (\epsilon_r + 1)$ d. $\chi_e = (\epsilon_0 + \epsilon_r)$
11. Electronic polarization
a. decrease with increase of temperature b. increases with temperature
c. may increase or decrease with temperature d. is independent of temperature
12. At normal temperatures, the polarizations which are independent of temperature are
a. electronic and ionic b. ionic and orientational
c. orientational and space charge d. space charge and electronic

MAGNETIC MATERIALS**Introduction:**

- Magnetism is the phenomenon by which materials bring attractive or repulsive forces on other materials.
- Magnetic fields are normally caused by movement of electrons.
- In a bar magnet, magnetic field is due to moving electrons which are circulating around the nuclei of atoms and spinning about their own axis. Atoms like this are said to possess a magnetic moment.
- The average field strength due to these moments at any particular point is called Magnetization (M).
- In most materials the moments are oriented almost at random which leads to weak magnetization and non magnetic properties. In iron moments readily align themselves along the applied field, including large values of M.
- Magnetics have wide range of application in electrical machinery and in magnetic tapes in computers.

Definitions:

1. **Magnetic field:** The space around a magnet in which its magnetic force is experienced is called magnetic field of that magnet. It is a scalar quantity.
2. **Magnetic dipole:** A system consisting of two equal and opposite magnetic poles separated by a small distance is called a magnetic dipole.

Or

Two poles of equal strength separated by a very small distance are called a magnetic dipole.

3. **Pole strength (m):** The ability of a magnetic pole to attract or repel another magnetic pole is called its pole strength.

SI unit A-m

4. **Magnetic moment (μ):** The product of pole strength (m) and length of a bar magnet (l) is called magnetic moment.

$$\mu_m = m \times l$$

In case of current carrying conductor, it is the product of current (i) and cross sectional area (A) of the conductor.

$$\mu_m = iA$$

It is a vector quantity. Its direction is from south pole to the north pole.

SI unit is Am^2

5. **Permeability (μ):** Property of a medium which allows the magnetic lines of force to pass through them.

It is also defined as the ratio of magnetic induction to magnetic field intensity.

SI unit is Hm^{-1}

6. **Relative permeability (μ_r):** Ratio of permeability of medium to permeability of free space.

$$\mu_r = \frac{\mu}{\mu_0}$$

It is purely a number, it has no units.

The permeability of free space or vacuum is $\mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1}$

7. Magnetic flux (Φ): The total number of magnetic lines of force passing normal to a surface in a magnetic field is called magnetic flux.

Its SI unit is weber

8. Magnetic field induction or magnetic flux density (B): The magnetic flux passing through a unit normal area of substance is defined as magnetic flux density and is denoted by B. It is commonly known as magnetic induction. Let Φ be the flux passing through a substance of area A, then flux density is

$$B = \frac{\Phi}{A} = \frac{F}{m}$$

It is a vector quantity.

Its SI unit is weber/m² or tesla and CGS unit is gauss.

1 tesla = 10^4 gauss.

9. Magnetic field strength or Magnetizing force or Magnetic field intensity (H): The force acting on a unit north pole placed at the point. It is independent of the medium.

$$B = \mu H$$

It is a vector quantity. Its SI unit is Am^{-1} .

10. Intensity of Magnetization (M or I):

It is defined as Magnetic moment per unit volume of a substance

$$M = \frac{\mu_m}{V} = \frac{m2l}{A2l} = \frac{m}{A}$$

It is defined as pole strength per unit area.

SI unit is Am^{-1}

11. Magnetic Susceptibility (χ):

Ratio of intensity of magnetization (I) to magnetic field intensity (H)

$$\chi = \frac{M}{H} \dots\dots (1)$$

Relation between B, H and M:

$$\begin{aligned} B &= \mu H \\ &= \mu_0 \mu_r H \\ \text{i.e., } B &= \mu_0 \mu_r H + \mu_0 H - \mu_0 H \\ &= \mu_0 H + \mu_0 H (\mu_r - 1) \\ &= \mu_0 H + \mu_0 M \end{aligned}$$

Where, M is magnetization = $H(\mu_r - 1)$
i.e., $B = \mu_0(H + M)$ -----(2)

The first term on the right side of Eq. (2) is due to external field. The second term is due to the magnetization.

Hence

$$\mu_0 = \frac{B}{H+M}$$

Relative Permeability,

$$\begin{aligned} \mu_r &= \frac{\mu}{\mu_0} = \left(\frac{B}{H}\right) / \left(\frac{B}{H+M}\right) \\ &= \frac{H+M}{H} = 1 + \frac{M}{H} = 1 + \chi \\ \therefore \mu_r &= 1 + \chi \text{ -----(3)} \end{aligned}$$

Q) Explain the origin of magnetic moment. Find the magnetic dipole moment due to orbital and spin motions of an electron?

Or

What is Bohr magneton? Derive expression for Bohr magneton?

Origin of Magnetic Moment:

In atoms the permanent magnetic moment can arise due to the following:

1. Orbital magnetic moment of the electrons.
2. Spin magnetic moment of the electrons.
3. Spin magnetic moment of the nucleus

The orbital magnetic moment of the electrons (μ_l) - Bohr magneton (μ_B):

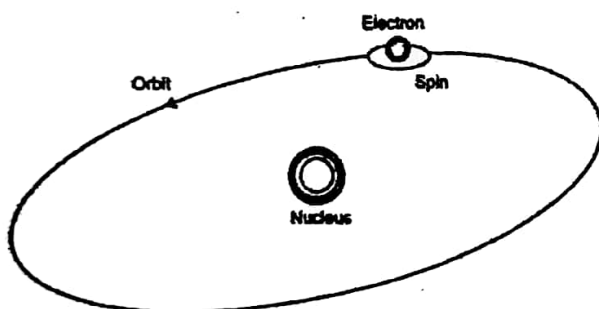
The magnetic moment contributed by a single electron is known as Bohr Magnetron.

Mathematically it can express as

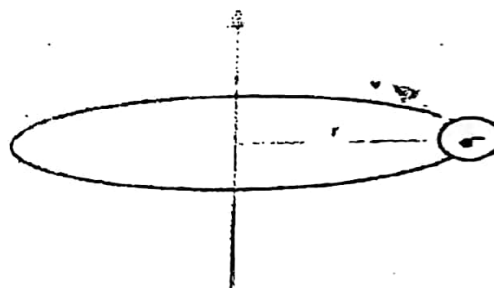
$$\mu_B = \frac{e\hbar}{2m} = \left(\frac{-eh}{4\pi m} \right)$$

Proof:

Let us consider an electron revolving in a circular orbit of radius r with a speed v . Consider a point p on the circle. The electron crosses this point once in every revolution. In one revolution the electron travels $2\pi r$ distance.



The orbit of a spinning electron about the nucleus of an atom



Motion of electron in a orbital

The current i due to the electron motion in the circular loop (orbit) is

$$i = \frac{\text{Charge of electron (q)}}{\text{Timeperiod (T)}} = \frac{-e}{T}$$

Where, T is time for one revolution of electron about the nucleus.

$$T = \frac{2\pi}{\omega} \text{ and } i = \frac{-e}{2\pi}$$

The magnetic moment μ_l associated with the orbit due to orbital motion of electron is

$$\mu_l = iA$$

Where, ' i ' is current produced by the orbital motion of the electron and A is area covered by the orbital (πr^2).

$$\mu_l = \left(\frac{-e\omega}{2\pi} \right) (\pi r^2) = \frac{-er(r\omega)}{2} = \frac{-erv}{2}, \text{ here } v = r\omega$$

Dividing and multiplying above eq. by the mass of the electron

$$\mu_l = \left(\frac{-e}{2m} \right) (mvr) = \left(\frac{-e}{2m} \right) (L)$$

We know that, the angular momentum of an electron revolving in circular orbit is equal to integral multiple of $\frac{h}{2\pi}$

$$L = mvr = l \frac{h}{2\pi}$$

$$\mu_l = \left(\frac{-eh}{4\pi m} \right) (l)$$

Where $l = 0, 1, 2, \dots$ = Orbital quantum number

$$\mu_l = (\mu_B)(l)$$

Here μ_B is Bohr magneton = $\left(\frac{-eh}{4\pi m} \right) = 9.27 \times 10^{-24} \text{ A-m}^2$

Here - sign indicates that magnetic moment is anti parallel to the angular momentum L .

Magnetic moment due to electron spin (μ_s): The magnetic moment associated with spinning of the electron is called spin magnetic moment μ_s . The net magnetic moment would depend upon the structure of the electron and its charge distribution.

$$\mu_s = \gamma(e/2m)S \text{ -----(1)}$$

where, $S = h/4\pi$ is spin angular momentum, γ is gyromagnetic ratio.

Therefore $\mu_s = 9.4 \times 10^{-24} \text{ A-m}^2$

Magnetic moment due to nuclear spin (μ_n): Another contribution may arise from the nuclear magnetic moment. By analogy with Bohr magneton, the nuclear magneton arises due to spin of the nucleus. It is given by

$$\mu_n = eh/4\pi m_p$$

$\mu_n = 5.05 \times 10^{-27} \text{ A-m}^2$. Where m_p is mass of proton.

The nuclear magnetic moments are smaller than those associated with electrons.

Q) Explain the classification of magnetic materials.

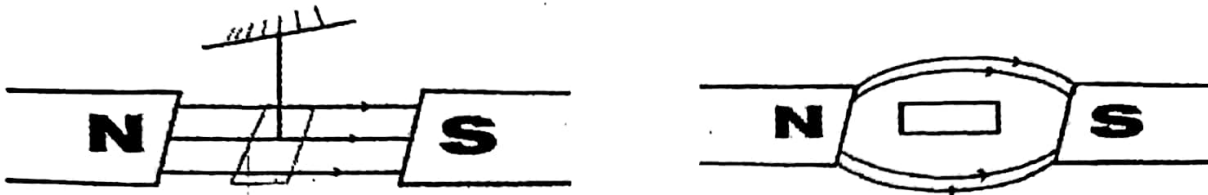
Classification of magnetic materials:

The types of magnetic materials can be studied depending on atomic dipoles and interaction between them.

- The first distinction is based on permanent magnetic dipoles.
- Materials which have no permanent dipoles are called Diamagnetic materials.
- The second distinction is based on interaction of dipoles.
- Materials which have permanent dipoles and no interaction between them are called Paramagnetic materials.
- Materials which have interaction among permanent dipoles of equal magnitude such that they align parallel are called Ferromagnetic materials.
- Materials which have interaction among permanent dipoles of equal magnitude such that they align antiparallel are called Anti Ferromagnetic materials.
- Materials which have interaction among permanent dipoles of unequal magnitude such that they align antiparallel are called Ferrimagnetic materials.

Diamagnetic materials:

An electron moving around the nucleus results in magnetic moment. When an external magnetic field is applied, the motion of electrons in their orbits changes resulting in induced magnetic moment in a direction opposite to the direction of applied field.

**Properties:**

- Permanent dipoles are absent.
- It is a weak effect.
- When placed inside a magnetic field, magnetic lines of forces are repelled.
- Susceptibility is always negative and is independent of temperature and strength of applied magnetic field.
- Relative permeability is slightly less than unity.

Ex: Hydrogen, Bismuth and superconducting materials like Niobium etc.,

Paramagnetic materials:

- Each electron in an orbit has an orbital and spin magnetic moment. In the absence of field, these moments are in random directions.
- When external magnetic field is applied, all these dipoles tend to align in the field direction giving induced positive dipole moment.
- Paramagnetic properties are due to the presence of some unpaired electrons.

**Properties:**

- Paramagnetic materials possess permanent magnetic dipoles.
- When placed in a magnetic field, it attracts the magnetic lines of force.
- Susceptibility is positive and depends greatly on temperature. $\chi = C/T$, C is Curie constant.
- Relative permeability is slightly greater than unity.
- Susceptibility is independent of applied magnetic field strength.
- Spin alignment is random.

Ex: Alkali metals, transition metals, chromium and yttrium, magnesium, molybdenum, lithium, and tantalum.

Ferromagnetic materials:

Certain materials like Fe, Co, Ni and certain alloys have high degree of magnetization and these materials have magnetization even if the external magnetic field is zero. These substances are called ferromagnetic materials.

Properties:

- When placed inside a magnetic field, it strongly attracts the magnetic lines of force.
- Each ferromagnetic material has a characteristic temperature called the ferromagnetic Curie temperature, $\chi = C/(T - \theta)$, C is Curie constant, θ is called Curie temperature.

- When $T > \theta$ ferromagnetic material is converted into paramagnetic material.
- Relative permeability is largely greater than unity.
- Susceptibility is large and positive.
- Spin alignment is parallel in the same direction.
- Exhibits Hysteresis.
- Consists of small regions which are spontaneously magnetized.

Ex: Fe, Ni, Co, MnO, Fe₂O₃

Antiferromagnetic Materials:

In certain materials when the distance between the interacting atoms is small, the exchange forces tend to antiparallel alignment of electron spins of neighboring atoms.

Properties:

- Antiferromagnetic susceptibility depends greatly on temperature.
- Susceptibility is small and positive.
- The important characteristic feature is occurrence of sharp maximum in susceptibility Vs temperature.
- The temperature at which this maximum occurs is called Neel's temperature.
- Above Neel's temperature, $\chi = C/(T + \theta)$, θ is paramagnetic curie temperature.
- Susceptibility slightly increases with temperature and beyond Neel's temperature it decreases with temperature.
- Spin alignment is antiparallel.

Ex: MnO, NiO, MnS, MnCl₂,etc

Ferrimagnetic materials (Ferrites):

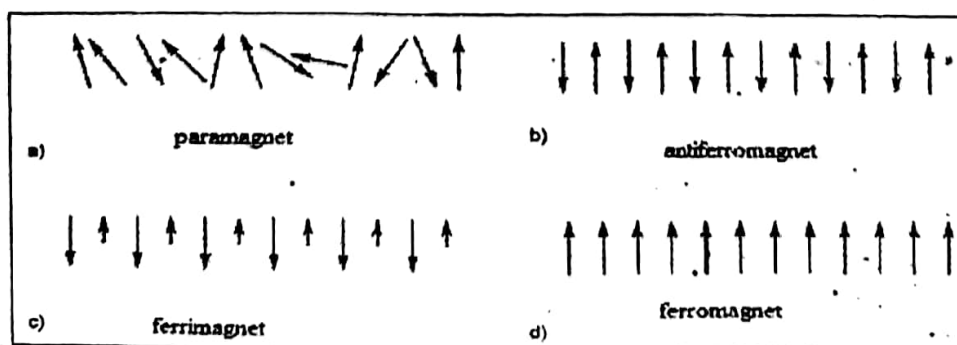
In these materials the net magnetization is not zero due to antiparallel moments of unequal magnitude. This moment disappears above a curie temperature similar to Neel temperature.

Properties:

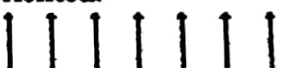
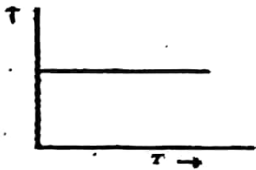
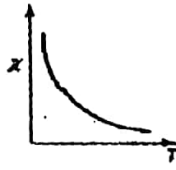
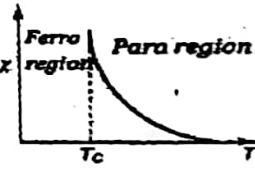
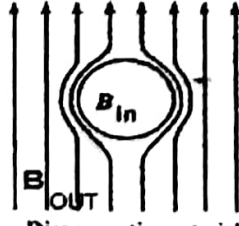
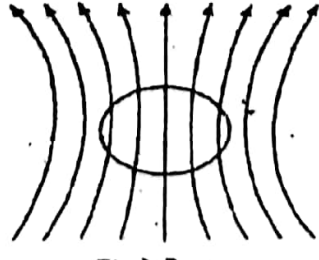
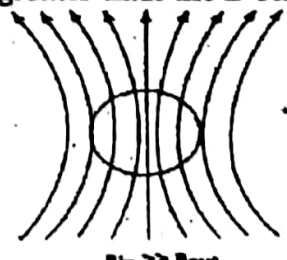
- Above Curie temperature the material becomes paramagnetic and below Curie temperature the material behaves as ferrimagnetic.
- Susceptibility is very large and positive.
- Above Neel's temperature $\chi = C/(T \pm \theta)$
- Ferrimagnetic domains become magnetic bubbles which act as memory elements.

Ex: Fe₃O₄, NiFe₂O₄, (MnMg) Fe₂O₄

Applications: These are used in electrical engineering because below certain temperature they behave as ferromagnetic and coming to their conductivity they behave as semiconductors. They can be used as transformer cores for frequencies upto microwaves. Ferrite rods are used in radio receivers.



Q) Explain the differences among dia, para and ferro magnetic materials.

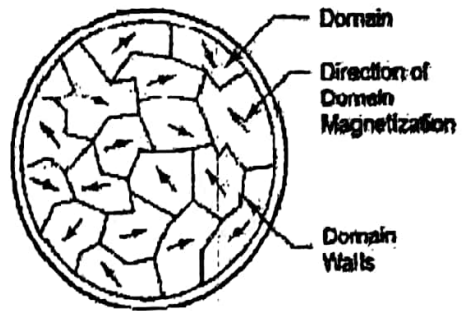
Property	Dia magnetic substances	Para magnetic substances	Ferro magnetic substances
Defination	The substance in which the resultant magnetic moment of individual atoms is zero.	The substance in which the resultant magnetic moment of individual atoms is not zero.	The substance in which the resultant magnetic moments of individual atoms align themselves in parallel by giving rise to spontaneous magnetization
Cause	Orbital motion of electrons	Spin motion of electrons	Formation of domains.
Relative Permeability (μ_r)	< 1	> 1	$\gg 1$
Susceptibility (χ)	Low and negative	Low and positive	High and positive
χ depend on T	Does not depend on T, except Bi at low T.	$\chi = C/T$ (curie law) C is curie constant.	$\chi = C / (T - T_c)$: $T > T_c$ (curie wises law) T_c is curie temperature.
Spin alignment	No spin alignment is present.	All spins or magnetic moments are randomly oriented. 	All spins or magnetic moments are orderly oriented. 
$\chi - T$ curve			
Transition of material at T_c	Do not change	On cooling these are converted into ferro magnetic material.	Converted into para magnetic material above T_c .
In the presence of magnetic field.	The magnetic lines of force are pulled out from the material. Hence, magnetic flux density is greater, outside the material than inside.  Diamagnetic material	The magnetic lines of force are attracted towards the centre of the material and hence the B_{in} material is greater than the B_{out} .  $B_{in} > B_{out}$	The magnetic lines of force are highly attracted towards the centre of the material and hence the B_{in} material is very greater than the B_{out} .  $B_{in} \gg B_{out}$
Example	Bi, Zn, H_2O , Gold.....	Al, Pt, Mn, $CuCl_2$	Fe , Ni, Co, MnO , Fe_2O_3 ...

Q) Explain the domain theory or Weiss theory of ferromagnetism.

Domain theory of ferromagnetism:

The concept of domains was proposed by Weiss in order to explain the properties of ferromagnetic materials and their hysteresis effects.

Magnetic Domains: Every ferromagnetic material is made of a very large number of miniature (very small) regions which are known as domains. The boundaries separating the domains are called domain walls, also known as Bloch walls. In each domain the magnetic dipoles align parallel to each other and produce spontaneous magnetization. The direction of spontaneous magnetization varies from domain to domain.



Process of Domain magnetization:

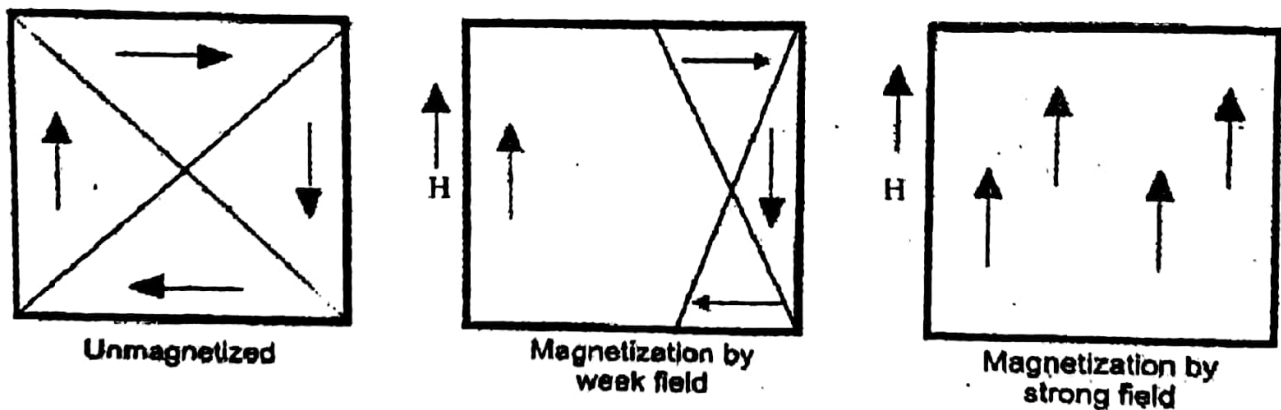
When the external field is applied there are two possible ways of alignment of random domains.

1. By the motion of domain walls.
2. By rotation of domains.

Motion of Domain walls: When a small amount of magnetic field is applied on a ferromagnetic material then the domains of the material whose magnetic moments are parallel or nearly parallel to the direction of applied field can grow in size where as the domains are not parallel to field can diminish in size. This change produces large magnetization for the bulk material.

Rotation of Domains:

When the magnetic field is increased further to a large value (i.e., near saturation), further domains growth becomes impossible and hence fully grown domains can rotate into the field direction and specimen is said to be saturated.



Magnetization of a ferro magnetic material

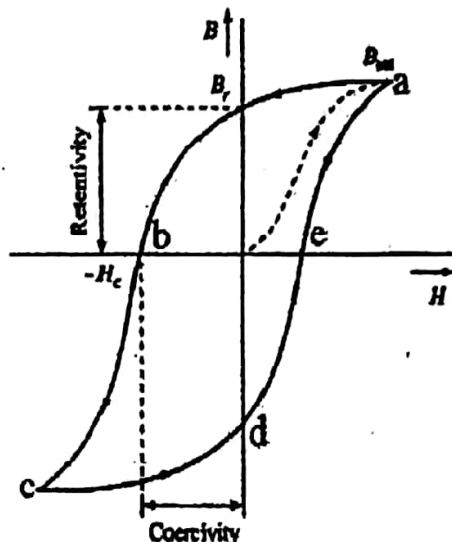
Q) Explain the hysteresis curve on the basis of domain theory.

Hysteresis curve:

Lagging of an effect behind the cause of the effect [or] the phenomenon of lagging B behind H is called hysteresis.

Explanation: When the magnetic field H is applied on an unmagnetized ferromagnetic material the magnetic induction increases first rapidly and then slowly from o to a. The increase is non linear, after that the rate of induction slows down and attaining a saturation value B_{sat} , with further increase in H, there is no increase in B. If applied magnetic field H on the material is decreased at this stage, naturally B decreases and B will not travel in that initial path, creates a new path.

When H is reduced to zero, B does not vanish; the value of B that remains in the material is called as retentivity B_r or residual magnetization. To remove retentivity in the material sufficient magnetic field H_c is applied in opposite direction then the retentivity B_r becomes zero. This field is known as coercive field. On increasing H further B reaches saturation in the opposite direction denoted by 'c'. Then reducing H to zero B reaches 'd' and then increasing H in the positive direction B reaches again to B_{sat} and a curve is obtained. This completes a closed loop called hysteresis loop. It includes some area. This area indicates the amount of energy wasted in one cycle of operation.

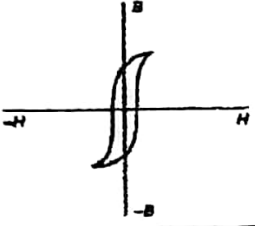
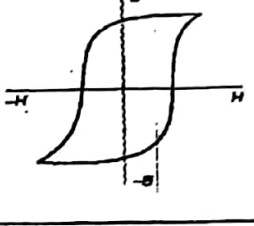


Q) Differentiate between soft and hard magnetic materials.

Soft and Hard magnetic materials:

Ferromagnetic materials are classified into two types based on the characteristic parameters such as hysteresis and magnetization. They are

1. Hard magnetic materials
2. Soft magnetic materials

S.No	Soft Magnetic Material	Hard Magnetic Material
1	Materials which can be easily magnetized and demagnetized are called Soft magnetic materials.	Materials which can't be easily magnetized and demagnetized are called hard magnetic materials.
2	The nature of hysteresis loop is very steep 	The nature of hysteresis loop is very large. 
3	They are prepared by annealing process.	They are prepared by quenching process.
4	Due to small hysteresis loop area, they have small hysteresis loss.	Due to large hysteresis loop area, they have large hysteresis loss.
5	They have large value of permeability and susceptibility.	They have low value of permeability and susceptibility.
6	The coercivity and retentivity are small.	The coercivity and retentivity are large.
7	Magnetic energy stored is less.	Magnetic energy stored is high.
8	They are free from irregularities.	They have large amount of impurities and lattice defects.
9	They are used > To produce temporary magnets. > In the preparation of magnetic core materials used in transformers, electric motors, magnetic amplifiers, magnetic switching circuits, etc.,	They are used > To produce permanent magnets. > In loud speakers, toys, in measuring meters, microphones, magnetic detectors, magnetic separators, etc.,
10	Ex: Iron and silicon alloys, Nickel-Iron alloy, Iron-Cobalt alloy.	Ex: High carbon steel, Cobalt steel, Barium ferrite.

Q) Write the Applications of Ferromagnetic materials.

Applications of Ferromagnetic materials:

- > There are a great variety of applications of the hysteresis in ferromagnets. Many of these make use of their ability to retain a memory, for example magnetic tape, hard disks, and credit cards. In these applications, hard magnets (high coercivity) like iron are desirable so the memory is not easily erased.
- > Ferromagnetism has its applications in transformers and electromagnets.

Questions

1. a) Define the terms
 - i) permeability ii) susceptibility iii) magnetic induction
 - v) intensity of magnetization vi) magnetic moment vii) magnetic polarizability
 b) Derive $B = \mu_0 (H + M)$
2. Explain the origin of magnetic moment. Find the magnetic dipole moments due to orbital and spin motions of an electron.
3. a) What is ferromagnetism and explain its properties.
 b) Explain the hysteresis curve on the basis of domain theory and hysteresis losses.
4. Explain the classification of magnetic materials and discuss their properties.
5. Differentiate between soft and hard magnetic materials.
6. Explain Weiss theory of ferromagnetic materials.

Problems

1. A paramagnetic material has a magnetic field intensity of 10^4 amp/m. If the susceptibility of the material at room temperature is 3.7×10^{-3} , Calculate the magnetization and flux density in the material.
2. Find the relative permeability of a ferromagnetic material if a field of strength 220 amp/m produces a magnetization of 3300 amp/m in it.
3. A magnetic material has a magnetization of 3300 amp/m and flux density of 0.0044 weber/m². Calculate the magnetizing field force and the relative permeability of the material. The permeability of vacuum is $4\pi \times 10^{-7}$ H/m.

Objective Questions

1. Magnetic permeability has units
 - a) weber/metre b) henry/metre c) amp/metre d) tesla/metre
2. The magnetic moment of free atom is due to
 - a) angular momentum of electrons b) spin of electrons
 - c) the induced magnetic moment by applied field d) all the above
3. The magnetic moment per unit volume is called
 - a) magnetic flux density b) magnetic field intensity
 - c) magnetic permeability d) intensity of magnetization
4. The magnetism exhibited by all materials is
 - a) dia b) para c) ferro d) ferri
5. Spontaneous magnetization is present in
 - a) diamagnets b) paramagnets

- c) ferromagnets d) antiferromagnets
6. The magnetization per unit magnetic field intensity is called
a) magnetic flux density b) magnetic permeability
c) magnetic susceptibility d) magnetic moment
7. The external magnetic field induces magnetic dipoles
a) only in diamagnetic materials b) only in paramagnetic materials
c) only in ferromagnetic materials d) all the above
8. The magnetic susceptibility is positive and small for
a) diamagnetic materials b) para magnetic materials
c) ferromagnetic materials d) antiferromagnetic materials
9. In soft magnetic material
a) coercivity is small and retentivity is large b) coercivity and retentivity are large
c) coercivity is large and retentivity is small d) coercivity and retentivity are small
10. Hard magnetic materials have
a) large hysteresis loop area b) small hysteresis loop area
c) zero hysteresis area d) optimum hysteresis area
11. Materials do not having permanent magnetic dipoles are
a. paramagnetic b. ferromagnetic c. ferrimagnetic d. diamagnetic
12. Relative permeability is related to magnetic susceptibility by
a. $\mu_r = 1 - x$ b. $\mu_r = x - 1$ c. $\mu_r = 1 + x$ d. $\mu_r = 1/x$
13. The transition from the ferromagnetic to the paramagnetic state is named after
a. curie b. curie-Weiss c. Neel d. Debye
14. One Bohr magneton is equal to
a. $4\pi mh$ b. $h/4\pi m$ c. $4\pi m/h$ d. $m/4\pi h$
15. Paramagnetic susceptibility varies as
a. T b. T^2 c. $1/T$ d. $1/T^2$